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Holocene environmental changes in the Gebel Umm Hammad, Eastern Desert, Egypt

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Abstract

Gebel Umm Hammad in the Red Sea Mountains east of Quseir, Egypt, today enjoys small but irregular amounts of winter rain, enabling the widening of joint controlled openings in the Thebes Limestone. Cavities are especially affected by flaking, while rock fragmentation is more active on the outside. The sedimentological and botanical study of fan deposits at the outlet of a karstic shaft in the Tree Shelter showed the local Holocene environmental evolution. Three periods of different degree of aridity can be considered: (i) Before 8120 ± 45 BP (UtC-5389), bedload aggradation points to rare but occasionally heavy rains, lasting for several hours, attaining intensities of more than 76 mm/h and covering some 20 km^2. Wadi flash floods occasionally attained bankfull stage. (ii) Since 8120 ± 45 BP (UtC-5389), such heavy rains have not occurred in the Egyptian Red Sea Mountains. Instead, a more moderate but maybe wetter precipitation regime was established. The karstic shafts were active, and there was water and life in the desert. Two humid pulses can be distinguished within this period. The first occurs at ±8000 BP, the second between 6630 ± 45 (GrN-22560) and 6770 ± 60 BP (GrN-22562). (iii) After the last wet culmination, there was a gradual shift to drier conditions. Shortly after ±5000 BP, modern climatic conditions are believed to have been attained. Today, the occasional rain storms are less heavy than before ±8000 BP. Bankfull stage river floods do not occur. Instead, secondary channels are eroded in the wadi beds. The general arid character during the whole period and the inherent local and temporal variations in precipitation patterns might explain apparent aberrations between the palaeoenvironmental evolution of the Tree Shelter site and other remote study areas in Egypt and Sudan.

Keywords: dry karst; desert; Egypt; flaking; Holocene; palaeoenvironment; spheroidal weathering

1. Introduction

The Gebel Umm Hammad is a 200-m high hogback on the western shoulder of the synclinal Nakheil valley. The valley and Gebel, together somewhat more than 5 km wide, run parallel to the Egyptian Red Sea coast for a distance of about 30 km, 25 km inland from Quseir (Fig. 1). The hogback consists of Thebes Limestone, the last marine deposit before Red Sea proto-rifting began in Oligocene times (Purser et al., 1990). The Thebes Limestone formation contains several beds, 0.5 to 2 m thick, with intercalated 'conglomerates' of rounded chert nodules. Differential weathering and/or erosion con-

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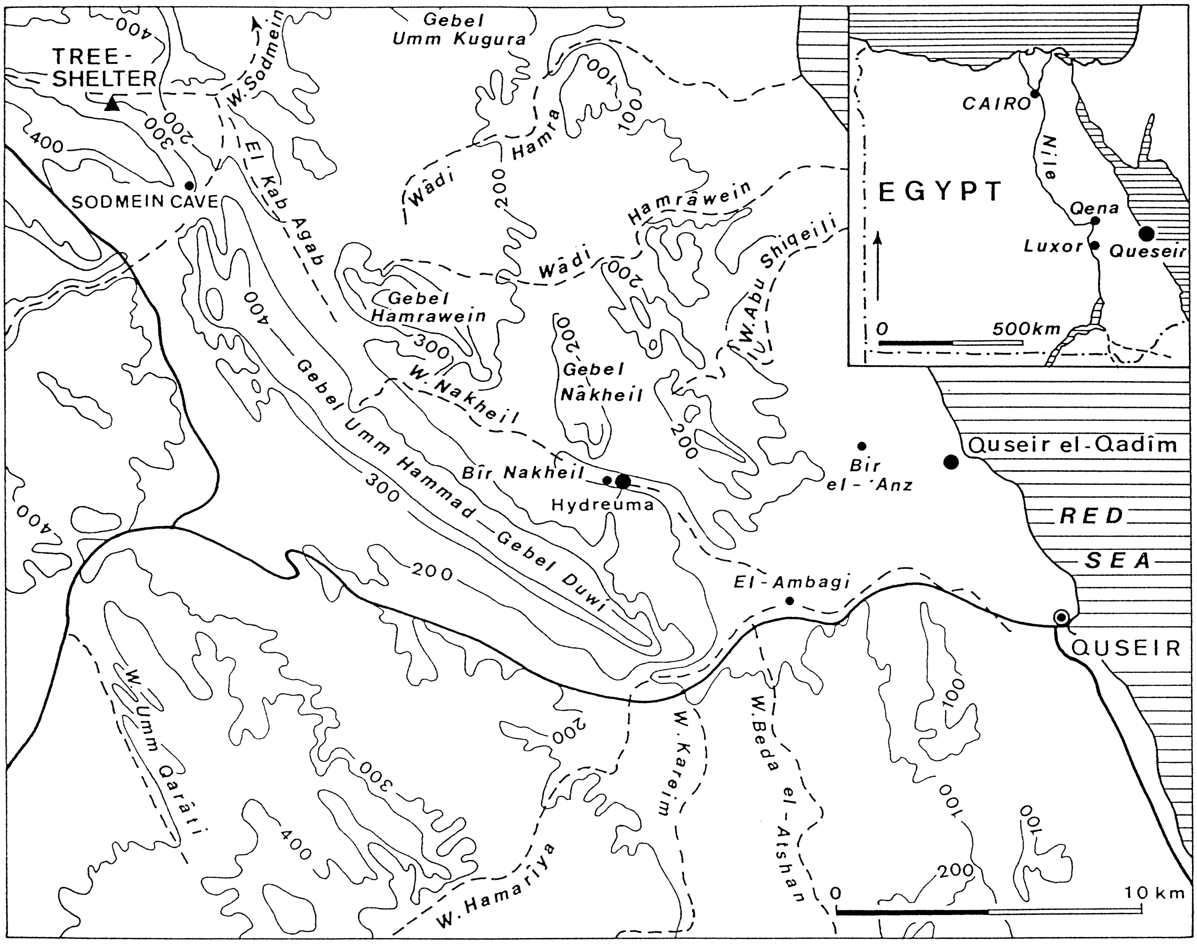

Fig. 1. Map of the study area.

tribute to the highly structural nature of macro-and micro-topography.

In several places, the Gebel dip-slope and associated flatirons show canyon-like wadi incisions by the resequent affluents of Wadi Nakheil and Wadi Sodmein. The first drains the major part of the synclinal valley and ends in the Red Sea at Quseir. Wadi Sodmein, on the other hand, has a consequent course: its drainage basin extends far west of Gebel Umm Hammad and cuts a more than 200 m deep gorge through the hogback front before turning to the north-east (Fig. 1) to reach the Red Sea some 30 km to the north.

Climatic conditions at Quseir are hyperarid with a mean annual precipitation of 4 mm and a mean maximum temperature of 28°C (Griffiths and Soliman, 1972). The irregular precipitation regime is marked by long, almost completely dry periods, that are interrupted by rare, high-magnitude events such as the storm in June 1934, a storm with 34 mm of precipitation (Planhol and Rognon, 1970). Stream floods and mass movements occur during such rare but extreme events and are the dominant landscape modelling processes.

Regular archaeological working visits since 1992 (Vermeersch et al., 1994) have revealed that the Gebel Umm Hammad receives some precipitation, according to our information, concentrated in the winter season: the Red Sea Mountains, although technically a desert, are apparently less dry than the

Red Sea coast at Quseir. In 1994–1995 and 1996–1997 in particular, winter rains were rather important and resulted in the deepening of erosional gullies in the wadi beds. Also several rock shelters in the Thebes Limestone appeared to produce some quantities of water and sediment during the winter rains and our first opinion that all the karstic phenomena in the Thebes Limestone are inactive today (Moeyersons et al., 1996) had to be revised.

2. Karst forms and processes in the Gebel Umm Hammad

Karst landforms, inherited from wetter geological periods in the past, have been described in Egypt (Said and Issawi, 1964), especially along the Red Sea coast south of Quseir (El Aref et al., 1986) and on the Eocene limestone plateau of El Bahariya oasis (El Aref et al., 1987). In both areas mature karst landscapes occur. In the Gebel Umm Hammad, surface karst phenomena are almost absent. Only along the Wadi Sodmein gap, we noted the presence of a possible solution doline, circular in form, about 10 m deep and 50 m wide. Below this depression there are several hollows and pipe networks, converging with depth. The phenomenon is probably related to a microtectonic graben obliquely crossing the gap.

Fig. 2. Ten to 15 m high canyonwall in Thebes Limestone in the vicinity of Tree Shelter, showing subvertical and subhorizontal galleries, located along vertical joints and bedding planes.

Fig. 3. Subhorizontal double shaft, developed along vertical joints and showing vertical blackish trails at the outlet, suggesting water outflow. Flaking spheroidal mantle visible below the orifices.

On the other hand, subsurface karst-like phenomena regularly occur in the Thebes Limestone on the Gebel Umm Hammad. They comprise openings and hollows along subvertical fissures and joints. Such cavities are either empty or filled with rubble and dust. On other occasions, subvertical shafts, sometimes a meter in diameter, are developed more or less in the joint plane (Fig. 2). Many widenings are probably joint-controlled corrosion kolks (Dreybrodt and Franke, 1994) in origin. Also horizontal tunnel-like phenomena occur in the Gebel Umm Hammad, like those in the base of the cliff in Fig. 2. Their diameter varies between some decimeters and several meters and even more. In some cases, black vertical trails suggest past or present outflow of water and dripstone-like pillars between roof and bottom sometimes appear (Fig. 3). Some of these galleries come from deep in the Gebel and have a widened outlet. Similar forms have been reported from the Atlas by Smith (1978). An example from the Gebel Umm Hammad is Sodmein Cave (Moeyersons et al., 1996). Travertine-like secondary deposits of $CaCO_3$ have been found deeper in the gallery, broken dripstones occur in the lower part of the shelter deposits and caliches are developed in some parts of the shelter infillings. We reported several of such caves in the area. Common to all existing karstic cavities in the study area is their control of location and form by vertical joints and fissures. The Tree Shelter below (Fig. 4) nicely illustrates the phenomenon.

Although $CaCO_3$ mobility at sometime in the geological past is manifest, the question arises if all

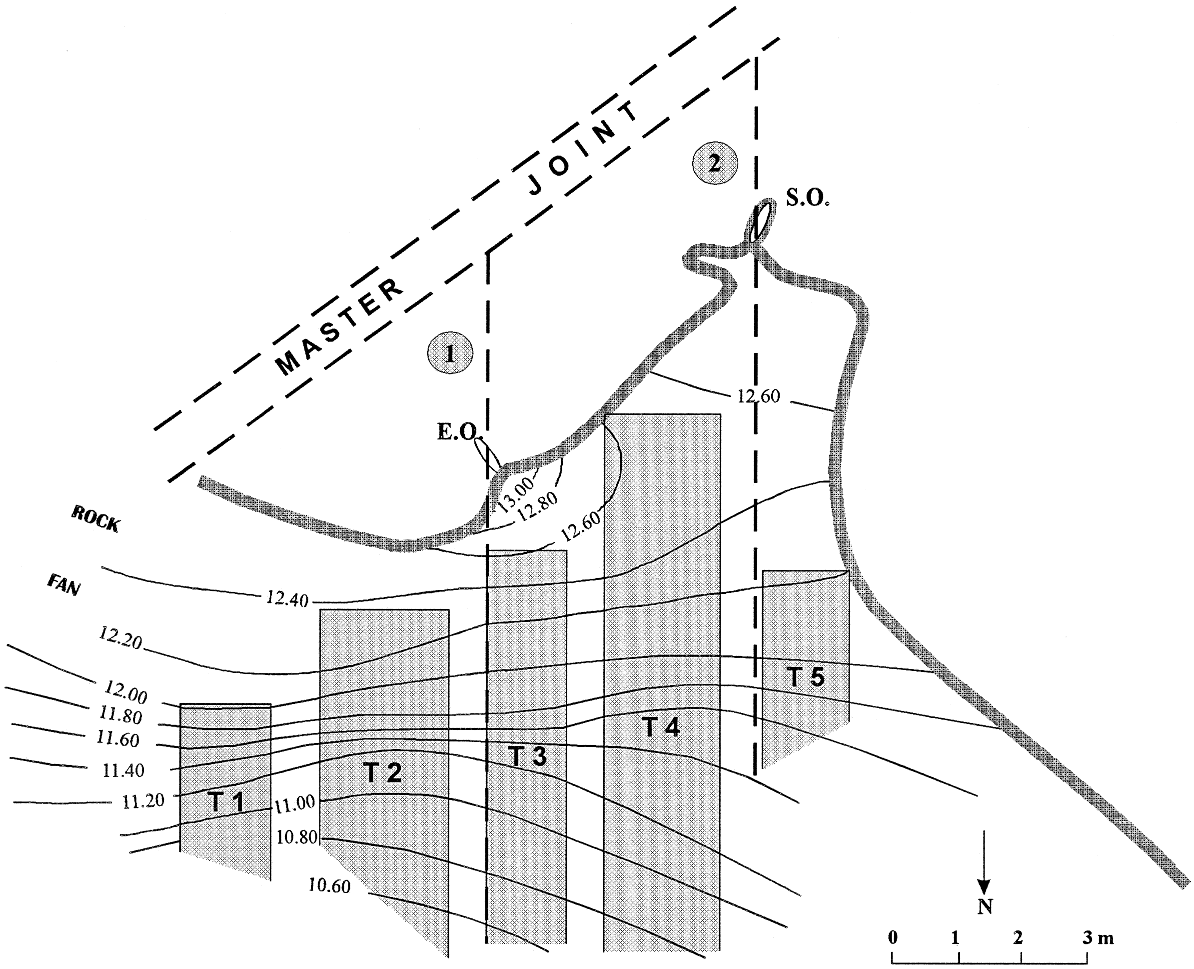

Fig. 4. Topographical map of the Tree Shelter. The presence of a few big rockfall debris from the roof is omitted. T 1 = trench 1; 12.60 = relative height in m; 1, 2 = secondary joints; E.O. = eastern orifice: S.O. = southern orifice.

Fig. 5. Spheroidal weathering around core stone in Thebes Limestone, in an incision in the Gebel Umm Hammad dipslope.

these subsurface hollow forms are purely solutional in origin. Today, Thebes Limestone, especially in karstic cavities, seems to undergo essentially mechanical breakdown. The most forthcoming process of visible rock weathering is peeling off by flaking (Fig. 3). Flakes are thin and flat, sometimes shell-like pieces of rock, mostly some centimeters wide and a few millimeters thick. Partly detached flakes on the walls and flake pieces on the ground provide evidence for this way of rock wasting. The process of flaking has to be related to the frequent occurrence of often well developed, flake producing spheroidal weathering mantles (Linton, 1955) in the Gebel Umm Hammad. On top of the dip slope, this mantle can be up to 1 m thick and nice examples of corestone outcrops exist along incisions (Fig. 5). Spheroidal weathering mantles are generally described around corestones, consuming fresh rock bodies from their outside. But the same flake bearing weathering belts can be rectilinear when they develop along a joint (Fig. 6). They can also develop in tubular form along primary seepage lines or weathering lines and start to consume the surrounding fresh rock from its inside. Many walls of subsurface cavities in the study area are still covered with in situ parts of such tube-like 'spheroidal' weathering mantles. Apparently these cavities owe their development to the flaking of the latter.

It is not clear whether spheroidal weathering on the Thebes Limestone in the Eastern Desert still develops today. As mentioned, it occurs sometimes over extensive surfaces and, if resulting from subsurface activities as believed by most authorities in the

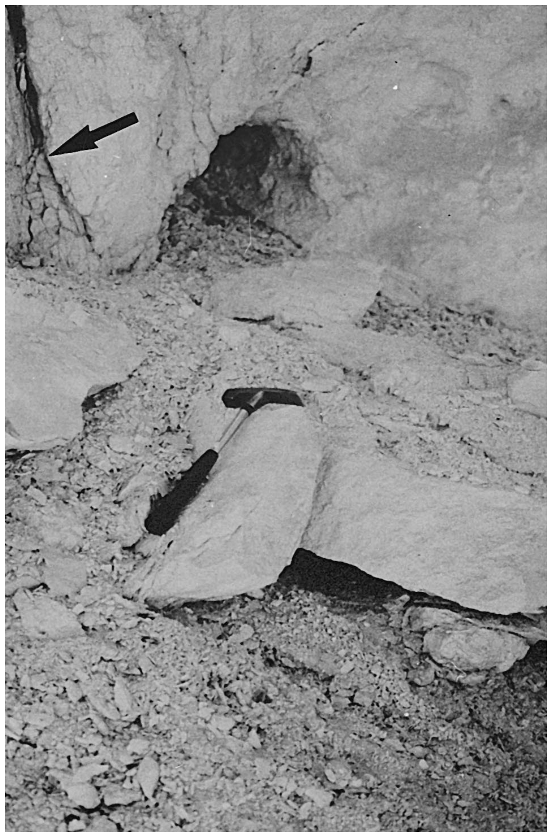

Fig. 6. The eastern orifice and part of secondary joint 1 (arrow and Fig. 4). The material supplied by the shaft consists meanly of flakes. The remnant of spheroidal weathering inside the pipe is visibly flaking off. Spheroidal weathering is also visible in the secondary joint 1 (arrow).

field (Twidale, 1982), would point to the existence of well developed soils during the geological past in the whole area. Important spheroidal weathering mantles also occur in El Bahariya Oasis (El Aref et al., 1987). We do not have additional information on the physico-chemical conditions for its development in limestone.

For the sake of completeness it has to be mentioned that the rock also breaks apart to rubble and boulders. Flakes, rock fragments and even rock walls seem also very prone to granular disintegration.

Samples of the natural weathering products of Thebes Limestone from the floor in Sodmein Cave and Tree Shelter (Fig. 1) have been compared with a completely HCl-decalcified Thebes Limestone handspecimen. The weight of the remaining artificial decalcification 'loam' amounted to about 35% of the weight of the treated piece of rock. According to Leighton and Pendexter (1962), the treated handspecimen should be qualified as an impure limestone. The artificial decalcification loam and the natural weathering products differ clearly in texture (Fig. 7). However, a common modus appears in the silt fractions between 63 and 32 μm. Microscopic examination shows that this fraction comprises essentially quartz grains of different forms and types and a certain number of silicified fossils in the decalcified Thebes sample as well as in the actual weathering product. The latter, however, is much less well-sorted due to the presence of angular to subrounded (Powers, 1953) Thebes Limestone fragments and also of very angular cherts in the sand (≥ 63 μm) fractions. This chert comes from chert nodules, present in the Thebes Limestone beds. Its fragmentation might result from mechanical disintegration, maybe initiated by rockfall, by salt weathering or by exceptional frost action. On the other hand, the Thebes Limestone sand fractions show very often microphenomena like smooth hollows, bulbs, and protrusions of insoluble inclusions, indicating somehow some degree of solution activities by CO_2 loaded water. Obviously, the Thebes Limestone seems to undergo solution but in

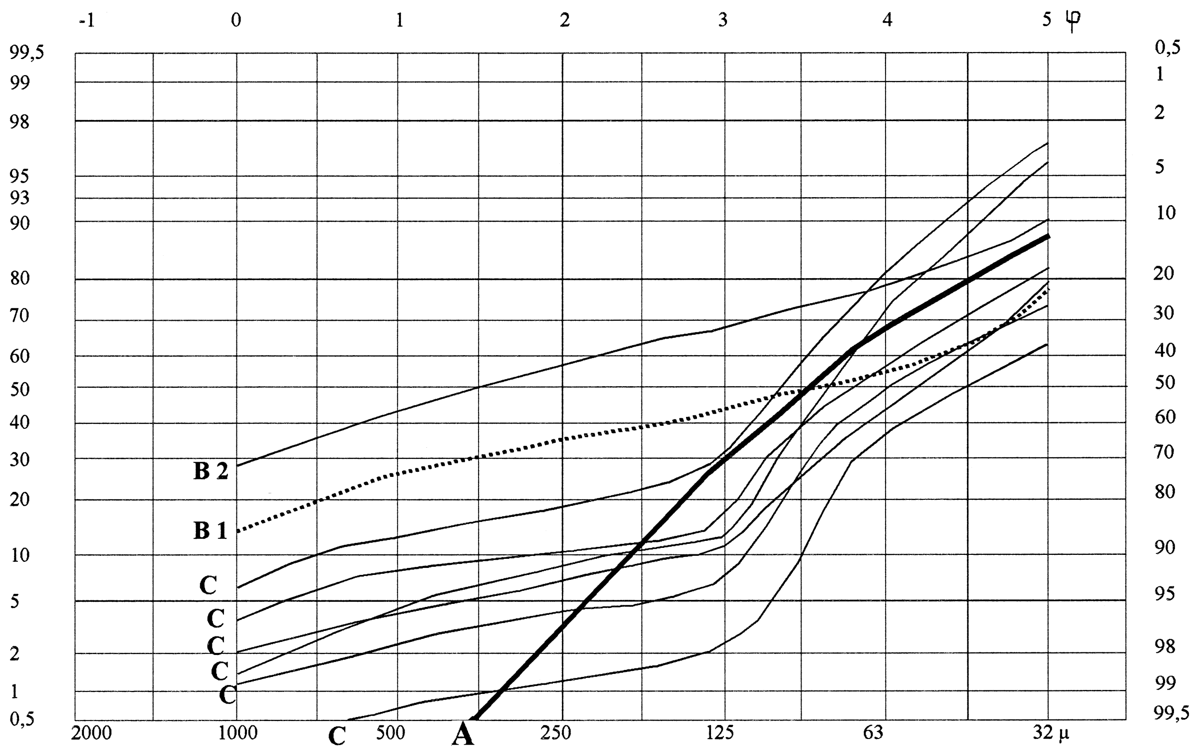

Fig. 7. Grain-size distributions. (A) Artificial decalcification loam of Thebes Limestone hand specimen from Sodmein; (B1) surficial layer in Tree Shelter, eastern orifice; (B2) Tree Shelter, matrix of colluvial deposit below fans; (C) surficial dust layer deep in Sodmein Cave.

the same time it falls apart in smaller pieces. The latter process does not necessarily result from classical mechanical rock weathering, but indirectly from solution. It has been observed under the binocular microscope that Thebes Limestone pieces, treated with HCl, react in two ways: the treated rock produces the above described decalcification silt, but part of the HCl disappears into small fissures and crevasses and soon sand and gravel sized Thebes Limestone fragments become detached from the rock specimen as a result of solution along the pre-existing joints. Therefore, joint and crack controlled solution might explain the bimodal grain-size distribution of the mineral weathering products in the upper layers in Sodmein Cave and Tree Shelter, and might explain the easy detachment of flakes from speroidal weathering mantles. It might be the process responsible for the karstic activities in the modern dry climate. Joint controlled solution in the absence of speleothems has also been attributed by Dreybrodt and Franke (1994) to climatic or environmental conditions without much vegetation. They argue that the low levels of CO_2 needed for the process are highly exceeded on soil covered surfaces bearing vegetation. The Gebel Umm Hammad hogback is largely devoid of any cover but receives still some winter rains and is, therefore, the ideal environment for joint controlled solution.

3. The Tree Shelter joint controlled karstic system

The Tree Shelter (Figs. 1, 4 and 8) is a local cliff foot recession, about 6 m deep, 4 m wide at its center and about 3 m high at the entrance. Its ground surface amounts to about 20 m^2. Both localisation and form of the shelter are highly structurally controlled. The shelter is developed over its entire height in a Thebes Limestone bed which is whiter and apparently also more friable than the overlying yellow-brown more massive bed, which forms the flat roof (Fig. 8). Fig. 4 shows the localisation and plan form of the shelter in respect to the present system of vertical joints. The most important, or head joint, is a 0.5 m wide and open subvertical fissure. It cuts the cliff obliquely (Fig. 4) behind the shelter. It starts on the top of the Gebel, 30 m higher, and passes on the apex of a rock fan, just downstream of the shelter, at the left side of the shelter on the photograph. The sides of the fan are covered by a mixture of dust and rock fragments, varying in size from gravel to boul-

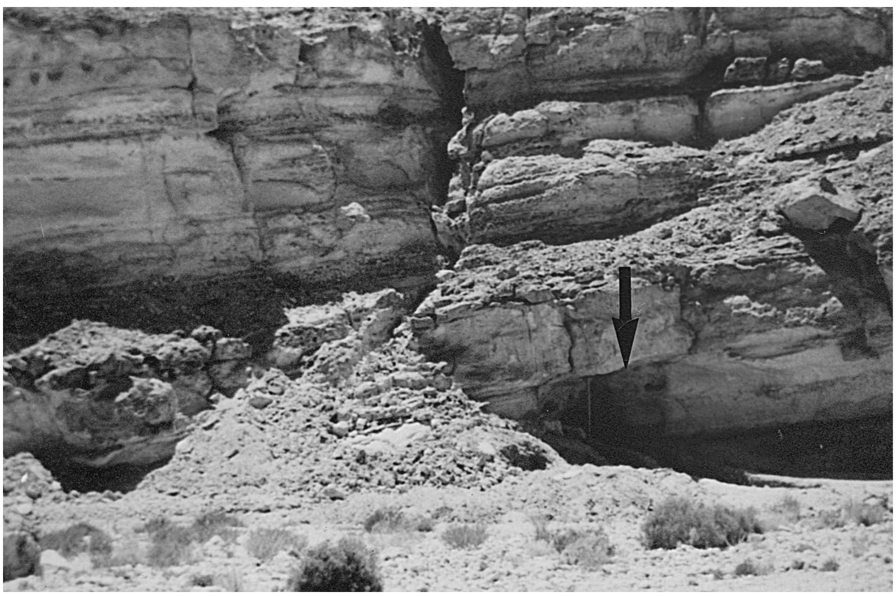

Fig. 8. Tree Shelter and the rock fan to the left. The master joint and the secondary joints in the overhang (Fig. 4) are visible. Wadi bed in foreground with high terrace along the rock fan and the shelter.

ders, forming a $\pm 32°$ slope, but two sections (trenches 1 and 2 on Fig. 4) into this material reveal a probable subhorizontal stratigraphy. Two secondary joints (1 and 2 on Fig. 4), clearly visible in the ceilings (Fig. 8), intersect the master joint and show some enlargements. Each intersection of the secondary joints with the shelter wall, gives rise to an orifice. During the 1994–1995 winter rains, both orifices were active. The southern one produced enough muddy water for small rills to develop on the apparently old debris fan. The eastern shaft produced a slaking mass of flakes and even bigger rock fragments (Fig. 6), forming a small fan on the gently northward dipping slope in the shelter (Fig. 4). The passage of water along joints apparently contributes to flaking and in this way to joint enlargement. In the dry environment of the Eastern Desert, places of water stagnation, like at the end of a vertical shaft, seem to undergo the highest rate of flaking and thus enlargement. As the shelter has been developed essentially along fissure 2 (Fig. 4), it might be possible that the shaft along fissure 1 has been activated much more recently than the southern shaft. As to the materials provided by the shafts in the Tree Shelter and in other cavities in general, their origin is difficult to identify. Given the existing connections with the surface of the Gebel, tens to hundreds of meters higher, the materials have the theoretical possibility to come from very far and to result from a long transport history. However, the material contains no typical surface forms like coated desert pavement elements, but, instead, comprises essentially flakes, considered to result from the further disintegration of underground spheroidal weathering mantles. Therefore, the material, supplied by the orifices, comes probably from the karstic galleries. The study of the fan deposits, to which their accumulation in the shelter gave rise at the two shaft outlets in the Tree Shelter provided some information on the geomorphological evolution of this remote and unknown area. The study was also promising from an archaeological point of view. Already during the reconnaissance tour in 1995, flint artefacts of Epipalaeolithic and Neolithic age were found to crop out on the shelter floor (Vermeersch et al., 1996). After Sodmein Cave, the Tree Shelter is the second prehistoric site in the Egyptian Eastern Desert, currently under study.

4. The deposits in the Tree Shelter

The deposits have been studied in five trenches (Fig. 4). Their most complete succession appears in trench 4. From top to bottom, three entities can be distinguished:

4.1. Fan deposits from the eastern shaft

At the orifice, they comprise flakes and bigger angular rock fragments (Fig. 6). In trench 4, the deposits are still 0.3 m thick, finer in texture (Fig. 7) and can be subdivided into six layers. The upper layer, ± 0.1 m thick, corresponds with the 1994–1995 winter rains. The underlying layers are respectively 0.06 m, 0.08 m, 0.06 m, 0.01 m and 0.05 m thick, and may each represent exceptional rainfall events. On the basis of the Quseir data, an important rain can be expected every 50 years, and thus the age of the fan can be estimated to be of the order of 300 years. Remarkably enough, the stratigraphy of the fan gradually fades with distance from the orifice and the fan thins out. Its thin superficial veneer in trench 5 contained a small hearth, ^{14}C-dated as 200 $\pm$ 35 BP (GrN-22559). This is in complete agreement with the supposed recent age of the fan.

4.2. Fan deposits from the southern shaft

The cone cross-section (Fig. 9) shows that the fan deposits dip away from the southern shaft with a slightly concave longitudinal slope, less than 2° from the horizontal. Therefore, the fan deposit is not considered as a solifluxion mudlobe, but as material laid down by runoff. The actual fan surface, being steeper, truncates the layering (Fig. 9). As observed after the 1994–1995 winter rains, rill erosion seems to be the process responsible for the truncation. It was probably active since about 4930 ± 30 BP (GrN-22561 date from charcoal from about 0.05 m below the top of the southern fan deposits). The reason for the change from accumulation to erosion is thought to reflect gradual wadi bed incision since that time. The southern fan deposits show no intercalations from the eastern shaft. They contain occasional rock debris of Thebes Limestone, but the body of the deposits is made up of flakes and sands and

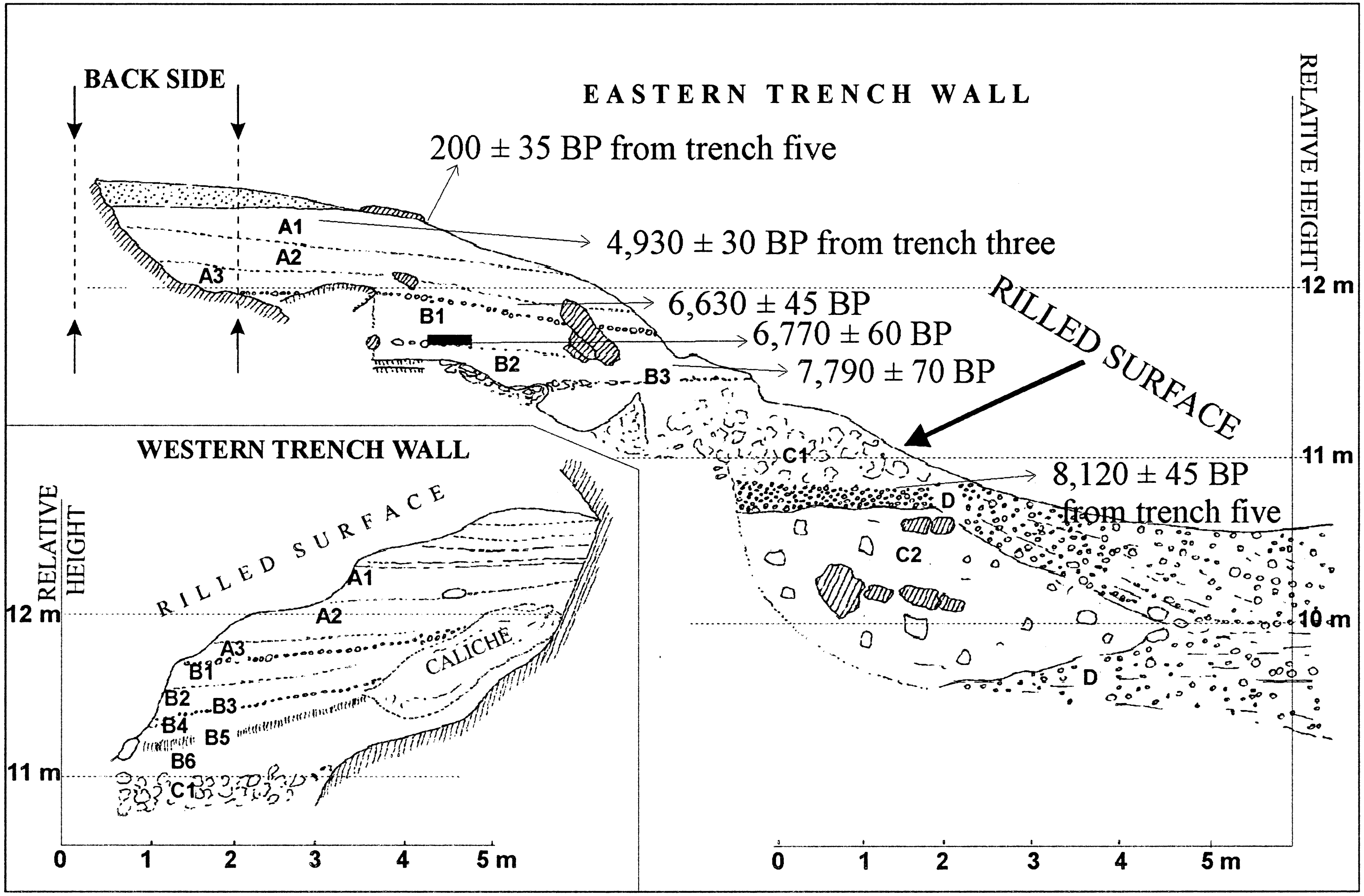

Fig. 9. Schematic drawing of sections in trench 4. Dates 6630 ± 45 BP (GrN-22560) and 7790 ± 70 BP (UtC-5388) are approximately located as indicated. Date 6770 ± 60 BP (GrN-22562) comes from a hearth and has to be related to the surface from where the hearth has been dug, 5 cm above the position of the dated charcoal. Dates 200 ± 35 BP (GrN-22559) and 8120 ± 45 BP (UtC-5389) occupy an equivalent stratigraphical position in trench 5 and date 4930 ± 30 BP (GrN-22561) in trench 3. All dates are quoted in radiocarbon years BP.

silts, resulting from the granular disintegration of the latter. The deposits can further be subdivided into two members:

- the upper A-member, with layers A1 to A3. The date of 4930 ± 30 BP (GrN-22561) comes from charcoal from a Neolithic hearth in the upper part of A1.
- the under-lying B-member, with layers B1 to B6.

Both members are separated by a somewhat coarser stone-line layer, not thicker than 0.01 m, containing somewhat bigger sized flakes and small rock fragments. A comparable layer, B3, separates B2 from B4. The question arises whether these two coarser layers are to be considered as lag-deposits upon erosive truncation. Two arguments can be forwarded to answer this question in a negative way. First of all, the actual erosion surface contains several rills, some of them more than 0.03 m deep. The 'stone-lines' on the other hand, appear in the trench walls as incisionless smooth and flat surfaces. Secondly, the submodern rilled erosion surface laterally truncates the much flatter lying fan deposits (Fig. 9), while the 'stone-lines' are exactly parallel with overlying and underlying deposits. Therefore, we consider these coarser 'floors' simply as a deposition from a runoff sheet with higher competence than above or below, necessarily as a result of bigger discharge.

The soil samples from both members show the same textural and microscopic characteristics as the eastern shaft deposits. Joint controlled solution in a dry environment seems still to be the case. But they contrast with overlying and underlying deposits in organic content: while the latter are quasi sterile, the A1 to A3 layers, and to a lesser degree the B1 to B4 layers, contain in their sand and silt fractions (2000–2032 μm) numerous pieces of charcoal, indeterminable plant and insect fragments and various types of other organic debris. On the whole, the A-members are slightly darker in colour (7.5YR 6/4 against 8/4) than the other deposits. In some places, nests of *Hymenoptera* are present and coproliths of faunal origin (Dorcas gazelle and others ?) are not uncommon. This, in combination with more competent runoff at the transition from A3 to B1 and at B3, suggests the presence of more faunal and floristic life and water in the southern fan deposits, especially in the A-member. Caliche development in the A- and B-members is a supplementary indication that water evaporation took place in the fan during an unidentified period in the past.

4.3. The lower blocky deposits with fluvial intercalations

Below the B6 layer, the material contains large (0.01–0.1 m) angular and subangular Thebes Limestone blocks and rock fragments. The matrix grain size distribution in C1 (Fig. 9) is given on Fig. 7. These blocky deposits contain intercalations of clearly fluvial material (D in Fig. 9), Thebes Limestone pebbles of variable dimensions, supplied by the wadi in front of the shelter. The highest intercalation corresponds in local elevation with the top of the 'high terrace', visible on Fig. 8 (Fig. 9). The colluvial rock debris C1 and C2 below the fan deposits have been deposited during a period of extreme wadi floods, giving rise to the aggradation of coarse and heavy bed load, the silts and fine sands being exported.

5. The deposits from the side of the rock fan, outside the shelter

Trenches 1 and 2 are situated outside, but very close to the shelter, in what was first believed to be a mere scree slope in rock debris on the flank of the rock fan (Figs. 4 and 8). The exposures in the trenches show essentially subangular Thebes rock fragments of variable size, sometimes clast supported, but in other places supported in the matrix of fine sand and silt. It appears that the stratigraphy in this material is essentially subhorizontal and cut by the 'scree' slope. The stratigraphy is comparable and perfectly correlated with the one inside the shelter. The blocky material on the flank of the rock fan contains in its upper 0.5 m a darker matrix of humic sands and silts. This layer has been related with the A-member of the fan deposits. Deeper, the matrix becomes more greyish and corresponds with the B-member. Although subdivisions like those in the shelter could not be seen, the artefacts from the B3 layer in the shelter did also occur in trenches 1 and 2 at about the same relative height of ±11.5 m, which confirms the stratigraphic continuity. The sections outside the shelter are important for two reasons: first, they show that the process of flaking was and is active, especially in the karstic shaft system of the Tree Shelter and in the cavity of the shelter itself, while contemporaneous processes outside lead and led more to boulder, block and debris formation, maybe the result of rock fall; secondly, the good correlation between fan stratigraphy in the shelter and debris stratigraphy, outside, suggest that the environmental changes, as recorded in the fan deposits inside a shelter or cave, reflect eventually in a very detailed way what happens outside.

6. The timing of events

Six uncalibrated ^{14}C dates on charcoal pieces (quoted here in radiocarbon years BP) provide a

Table 1
Fan growth dynamics, evolution of wadi bed and adjacent slopes and rainfall patterns since more than 8000 BP at Tree Shelter site (Egypt)

RADIOMETRIC AGE BP	SOUTHERN FAN		WADI	VALLEY SLOPES		PRECIPITATION REGIME	
0- to 5,000- (1,000-, 2,000-, 3,000-, 4,000-)		EROSION	CHANNEL INCISION IN WADI BED	RUNOFF EROSION		HYPERARID WITH LESS HEAVY RAINS THAN BEFORE 8,000 BP	
5,000- to 8,000- (6,000-, 7,000-)	± 0.35 mm/year ± 2.14 mm/year ± 0.32 mm/year ± 1.97 mm/year	DEPOSITION	NO TRACES OF BANKFULL STAGES. MORE REGULAR FLUVIAL REGIME?	gravel and boulder deposition and mass movements	higher humic content	wet peak wet peak	higher frequency of less heavy rains
8,000- to 10,000- (9,000-)			FLASH FLOODS AND BEDLOAD AGGRADATION			EXTREMELY HEAVY RAINS IN DRY ENVIRONMENT	

chronological framework for the southern fan deposits (Fig. 9). The charcoal fragments date the stratigraphical level at which they are found. An exception is date GrN-22562: the charcoal comes from 5 cm below the rim of a hearth, and corresponds in age with the surface from where the hearth has been dug. The Holocene age of the stratigraphic succession is evident (Fig. 9), but the geomorphological dynamics show remarkable variations. Cautious and conservative estimations of fan deposition rate, deduced from difference in altitude between the dated stratigraphic levels, are given in Table 1. The variations in deposition rate largely exceed the possible error by the use of radiometric ages. Shortly after 4930 ± 30 BP (GrN-22561), the activities of the southern orifice switch suddenly from accumulation to erosion, the latter apparently still active today. At the end of this erosive period, probably only some hundreds of years ago, the eastern shaft starts its own fan building. The southern fan deposits show two well pronounced peaks in deposition rate. The most recent one sits between 6630 ± 45 (GrN-22560) and 6770 ± 60 BP (GrN-22562) and comprises layers A3 to part of B1. It includes the stone-line-like transition between A- and B-member, discussed earlier. An older peak, between 7790 ± 60 BP (UtC-5388) and 8120 ± 45 BP (UtC-5389), concerns layers B2 to B6 and further the rocky C1 facies on top of the uppermost wadi deposits. The southern fan formation starts with a peak in deposition, the B3 stone-line about in the center. Peaks in fan deposition rate in this dry environment probably point to periods of more runoff. The intercalation of a stone-line in the middle of such a period, corroborates the hypothesis from above that the stone-lines within the fan deposits are depositional in nature and correspond to higher runoff competence. In the mean time, the small artefacts, found in and around such a stone-line would have undergone little or no post-depositional reworking.

7. The palaeoenvironmental context of the Tree Shelter

Several points, explained further in more detail, indicate an arid environment during the whole period of fan deposition since 8120 ± 45 BP (UtC-5389): the more or less catastrophic nature of precipitation regime during the whole period; the remarkable underground preservation of organic materials, indicating the essentially dry character of the environment through time; the spectrum of tree species, defined on the base of charcoal remains. Nevertheless, clear differences as to the degree of aridity appear: from before 8120 ± 45 BP (UtC-5389) till 4930 ± 30 BP (GrN-22561), subhorizontal accumulation of rock debris, gravels and sands took place in the wadi valley. Before 8120 ± 45 BP (UtC-5389), these deposits interfinger with coarse wadi bedload (Fig. 9). It concerns a period of bankfull and even overbark wadi stages, with a flood peak discharge estimated at *c* 40 m^3/s. The supposed wadi discharge peak of 40 m^3/s can easily be calculated to correspond with an input of a storm rainfall intensity of 72 mm/h over the 20 km^2 basin, again neglecting losses by evapotranspiration and infiltration. Such an intensity is not exceptional. Combined, however, with the second condition, namely that this intensity should cover the entire 20 km^2 basin during a time necessary to install steady state flow conditions in the whole basin, implies that it concerns in fact an extremely heavy rainstorm. Obviously, the high water stages, indicated by the stratigraphy, can only represent individual flash floods and not a seasonal or permanent situation. Concerning the periods between the floods, no evidence exists for a permanent wet and green environment.

The period of aggadational wadi floods came to an end with the establishment of the high wadi terrace just before 8120 ± 45 BP (UtC-5389). Subsequently, the subhorizontal accumulation of rock debris continued in the wadi side, but without anymore traces of fluvial inundations. Instead, very shortly after 8120 ± 45 BP (UtC-5389), we find the first fan deposits in the shelter. Maybe the shelter was scoured out by the wadi during the last high wadi stand, a process which might have liberated the already existant southern orifice (Fig. 4). Until about 4930 ± 30 BP (GrN-22561), flakes, sand and loam have been supplied at regular times by the latter and accumulated in the shelter as a small fan deposit, showing a gradual lateral transition into the subhorizontal coarse rock debris outside. Above the B5 layer, the fan contains organic material from plants, insects and animals. The concentration of organic debris becomes even higher in the A member. The whole period of southern fan development, but especially the period of the A member development, knew more precipitation than today because such rich organic, content is absent even in the base of the eastern fan deposits. On the other hand, rain storms of the size from before 8120 ± 45 BP (UtC-5389) did not occur anymore. It is supposed that the period of southern fan deposition represents conditions where joint controlled solution and especially flaking is active in the karstic pipes. Within these shafts, there was also transport to their outlet. Without any doubt, there was enough precipitation to realise at least partial water percolation from the gebel backslope through shafts and galleries with resurgence at the wadi side. However, precipitation was not evenly spread over the whole period. The two accumulation rate maxima in the souther fan deposits and the high competence runoff stone-lines within these maxima are interpreted as the expression of two more humid pulses within this long period. The oldest pulse is a rather short one and falls between 8120 ± 45 BP (UtC-5389) and 7790 ± 70 BP (UtC-5388), probably very close to 8000 BP. The younger pulse takes longer and is centered around the transition between A- and B-member between 6630 ± 45 BP (GrN-22560) and 6770 ± 70 BP (GrN-22562). Charcoal appeared in and around the deposits of both pulses. During the later pulse, it is generally found in hearths. The following wood species have been identified: *Capparis decidua* (Forsk.) Edgew., *Salvadora persica* L., *Acacia nilotica* (L.) Willd. *ex* Del., *Boscia salicifolia* Oliver., *Acacia tortilis* (Forsk.) Hayne., *Maerua crassifolia* Forsk., *Acacia albida* L., *Tamarix* sp. At the deposit of the wet pulse at ± 8000 BP, there are dispersed and fragmented charcoal pieces identified as *Tamarix* sp., *A. albida* L., *A. tortilis* (Forsk.) Hayne., *Celtis* sp., *Balanites aegyptiaca* Del., *A. nilotica* (L.) Willd. ex Del. It should be stressed that these botanic spectra are typical for dry conditions like steppe and dry savannah environments.

After the younger pulse and the subsequent relatively wet period, important changes occurred: the southern fan deposits in the shelter stopped growing and runoff, still fed occasionally by the pipe, started to erode and to laterally truncate the fan deposits. Its rock debris counterpart, outside, also underwent lateral erosion in the direction of the center of the wadi bed. The erosion process, inside the shelter as well as outside apparently continues today and points to a gradual reincision of the wadi bed, aggraded before 8120 ± 45 BP (UtC-5389). This reincision is thought to continue today at the occasion of exceptional rains. After the 1994–1995 winter rains it became clear that the modern rainstorms do not lead to complete wadi bed inundation but only to the scouring out of small secondary channels in the wide wadi beds. This situation seems thus to have prevailed over about the last 5000 years. Table 1 summarises the geomorphological and climatic events since some time before 8000 BP.

8. Local and regional comparison

Comparing the palaoenvironmental evolution between sites on the base of their stratigraphy is often difficult. One can never be sure that the stratigraphic record covers a complete time span. Stratigraphic hiatuses are not always detectable. Furthermore, local conditions might govern the stratigraphic expression of environmental characteristics. Finally, the local nature of precipitation regimes in arid environments might obscure existing similarities or differences between the palaeoclimatic evolution on different sites. Therefore, the palaeoenvironmental evolution, worked out above, might miss some pulsations, well expressed in other sites. In the same way the Tree Shelter might indicate pulsations not observed elsewhere.

The Holocene environmental evolution, established at the Tree Shelter (Table 1), has been compared with the results from Sodmein Cave, only 4 km to the southeast. Here, the Holocene layers B to D (Moeyersons et al., 1996) are ^{14}C dated between 6320 ± 100 BP (Lv-2082) and 7090 ± 80 BP (Lv-2086). They fall within the wet period, centered around the A–B-member transition in the Tree Shelter. The B to D layers in Sodmein contain charcoal fragments of *Cadaba farinosa* Forsk., *A. tortilis* (Forsk.) Hayne., *Salvadorica persica* L., *Tamarix* sp., *Boscia senegalensis* (Pers.) Lam. ex Poir., *Ziziphus* sp. Still more trees are present, but could not be identified. Indications for the most humid environment are given by the presence of *Olea* sp. in the C layer, approximately dated between 6360 ± 90 BP (Lv-2085) and 6940 ± 100 BP (Lv-2083), and thus overlapping the youngest wet peak in the Tree Shelter. No accumulations of the peak at 8000 BP have been found in Sodmein Cave. This period is presented by a stratigraphic hiatus and disconformity, due to erosion. The dry period since the last wet pulse is represented in Sodmein by a superficial dust layer, occasionally reworked by wind and rain.

The Holocene climatic and environmental evolution at the Tree Shelter has also been compared with the results by other workers in the wider region. The modern aridity in the Red Sea Mountains appears to have commenced maybe as much as 1000 to 2000 years earlier at the Tree Shelter than in Sudan, 500 to 1000 km to the south (Alaily, 1993; Hoelzman, 1993). On the other hand, studies on *Pteropoda* from the Red Sea (Almogi-Labin et al., 1991) show that before 8500 BP, i.e., during the period of high wadi floods, the mixed seawater layer and the salinity showed rapid variations, possibly associated with unstable conditions in the upper part of the water column. The period of extreme floods in the Gebel Umm Hammad might also correspond with the very first local rains after the 'Wild Nile' period, which was still dry in Egypt (Butzer and Hansen, 1968; Adamson et al., 1980; Butzer, 1980; Vermeersch, 1983; Paulissen, 1986; Paulissen and Vermeersch, 1989). ^{14}C dates from predynastic hearths and fossil root systems, combined with faunal and botanical evidence show that the Nile valley at Qena became wetter since ±9740 BP (Vermeersch et al., 1992). According to the same authors, humid conditions prevailed until ±6000 BP but it took until ±4810 BP before the Nile valley environment was again fully adapted to hyperarid conditions. The latest date from Tree Shelter before modern aridity is 4930 ± 30 BP (GrN-22561).

In the Eastern Sahara, west of the Nile, the two last humid pulsations in Nabta Playa and Bir Kiseiba, Playa II and III, (Wendorf and Schild, 1984) correspond closely in age with the ones from the Tree Shelter. However, these two sites are some 400 km further to the south. Correlations with the closer Kharga Oasis (Wendorf and Schild, 1980) are less clear.

On the other hand, clear parallels appear between Tree Shelter and Dakhla Oasis. Here, Brookes (1993) mentions a pluvial interval from about 9000 to 4500 BP. At Tree Shelter, the modern arid phase was dated to start shortly after 5000 BP.

According to Neumann (1989), a very dry environment prevailed in the Eastern Sahara north of 25°N since 6000 BP and became apparent in Gilf Kebir and Soudan around 5000 BP. In the North, the less dry period before 6000 BP saw a depauperate botanical spectrum.

More to the south, Kröpelin (1989) attributes wadi deposits in Gilf Kebir to an arid environment, prevailing during the whole of the Holocene era. He assumes that between 9500 and 6000 BP the area experienced about four heavy rainstorm events a century. More moderate aridity occurred between 6000 and 5000 BP, and supposed renewed aridity since 4800 BP is not documented any more by the deposits.

In the central Sahara, Pachur and Braun (1980) find a fluvial link between the Tibesti and the Mediterranean, radiometrically dated around 8000 BP, the moment of the first humid pulse at Tree Shelter. According to the same authors the period after 5000 BP shows a trend to decreasing precipitation. Another fossil fluvial link is the one between Wadi Howar and the Nile in Sudan. This wadi was active from about 9500 to 4500 years ago (Pachur and Kröpelin, 1987).

Finally, the compilation by Banks (1984) shows that results from the Tree Shelter differ markedly with the Holocene climatic evolution from more remote areas like the Tibesti and Hoggar massifs or like Lake Tchad.

This short overview evidences certain parallelisms between the evolution at different sites in the Eastern Sahara, the Red Sea Mountains and the Red Sea basin. All authors, mentioned, agree on the existence of a humid or less arid period in the first half of the Holocene. However, some pulsations or marked transitions in the climatic history at some sites are out of phase with the same characteristic points in the evolution at other sites. Part of this problem might be due to the restricted possibilities of finding ^{14}C datable quantities of charcoal at the desired stratigraphical levels. Another partial explanation might be the arid character of the whole region during the period considered, even as far south as Gilf Kebir (Kröpelin, 1989). The irregular precipitation in such conditions might explain the apparent aberration between the 'climatic' evolution from different sites.

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